

Project Report: An Astronomical Search for the Essential Ingredients for Life: Placing Our Habitable System in Context. Progress Report

Project Investigators:

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Project Progress

Module 1: Building Blocks of Life

This module has carried out a variety of laboratory, theoretical, and observational studies centered on the possibility that the ribose in DNA/RNA had an interstellar origin. The following sections detail this progress.

Laboratory Spectroscopy of Simple Sugars

Aldo Apponi is currently in the design/construction phase of a new spectrometer: a Fourier transform microwave system, which will be used to measure the pure-rotational spectra of simple sugars. This spectrometer will have exceptional sensitivity in gas-phase studies of such pre-biotic molecules because it utilizes a supersonic molecular beam source, a high finesse Fabry-Perot filter cavity and ultra low noise amplifiers. The basic design is completed, and the University instrument shop has built the vacuum chamber. The pumping system and electronics are on order. The completed cell should be ready by July 2004 with initial tests in August 2004.



Figure 1: Larry Acedo and Aldo Apponi posing next to the newly constructed vacuum chamber in the University Research Instrumentation shop at the University of Arizona . When complete, the cell will house a sophisticated system of optics, electronics and cryogenic equipment that will be used to study molecules important to rudimentary life on Earth.

Observational Studies of Molecular Clouds and Comets

Graduate student DeWayne Halfen is completing a radio astronomical investigation of glycolaldehyde. Additional observations have been conducted at the Arizona Radio Observatory's (ARO's) 12-m telescope at Kitt Peak to confirm a few spectral lines in SgrB2N that may have arisen from image contamination in previous measurements. Thus far, 25 very favorable rotational transitions have been unambiguously confirmed. The column density of glycolaldehyde in SgrB2N is calculated to be $N_{\text{tot}} \sim 10^{13} \text{ cm}^{-2}$. Success of this project indicates that more complicated sugars may be detectable in interstellar gas, provided the spectroscopy and quantum mechanics of the molecules are well understood.

Graduate student Stefanie Milam has conducted observations of comets Linear, Neat, and Bradfield. Formaldehyde, H_2CO , the basic precursor to ribose-like sugars, has been detected in these objects. Other sugars may be present as well. Furthermore, because comets appear to routinely disintegrate and fragment as they approach the sun, millimeter-sized grain-like particles containing organics are ejected into interplanetary space and probably end up in planetary atmospheres. Further investigation of archived data suggests organic, grain-like precursors for species such as HCO^+ and HNC in comet Hale-Bopp. Recent analysis of data taken of this comet indicates a possible secondary source, believed to be organic-rich, volatile grains as seen in Figure 2. These grains are easily fragmented to produce more common "cometary species" such as H_2CO and HCO^+ through photodestruction. (Milam, Savage,

Ziurys, and Wyckoff , *Ap. J* , in press).

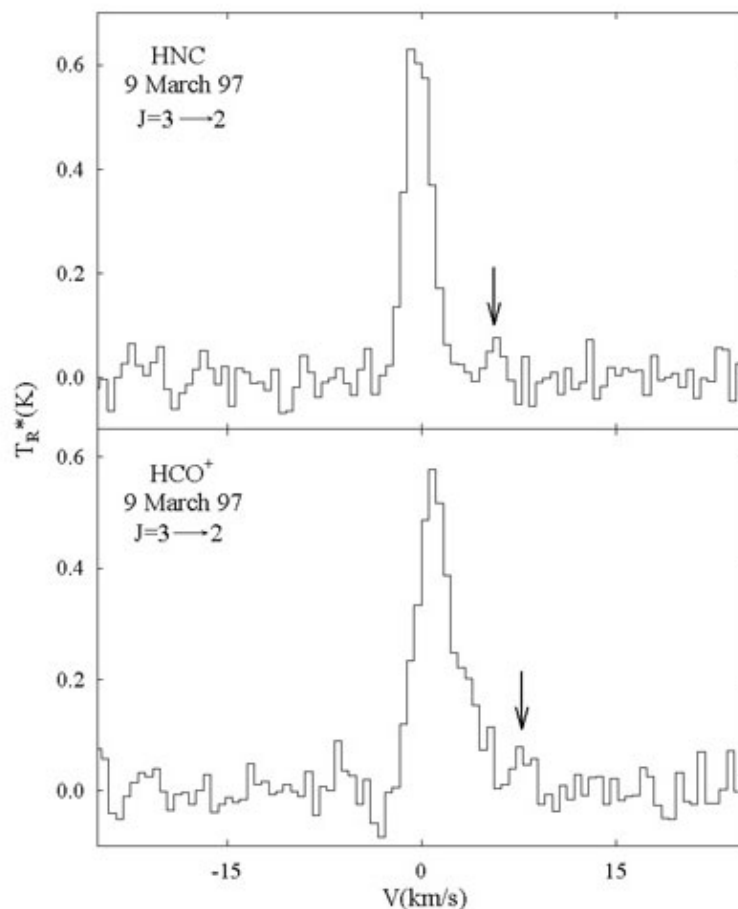


Figure 2: The J=3_2 transition of HCO⁺ at 268 GHz and the J=3_2 line of HNC at 272 GHz detected towards comet Hale-Bopp, using the Arizona Radio Observatory 12 m telescope on March 9, 1997, with 500 kHz (0.55 km/s) resolution. A second velocity component appears to be present in both spectra, shifted by about 5 km/s from the main line, indicated by arrows. Recent analysis suggests the secondary components likely arise from volatile, organic grains.

Gas-Phase Laboratory Organic Chemistry

Graduate students Ben Werner and Matt Judd have begun lab experiments to test whether the gas-phase reactions of H₂CO can lead to simple sugars. Their first task is to devise a suitable source of gas phase H₂CO. They have discovered that they can get a good stream of relatively pure formaldehyde gas at 50°C from paraformaldehyde with catalysis by tosyl acid. (Higher temperatures lead to disproportionation to produce a variety of compounds.) They have trapped the stream in deuteriochloroform, and have analyzed the resulting mixture by proton nuclear magnetic resonance (NMR). They are

presently trying to measure the rate of trimerization to trioxane in deuteriochloroform, which is actually reasonably slow. Additionally, they are looking at ways to generate a gas phase stream of the 2-carbon sugar from aqueous solution.

Quantum Mechanical Calculations of Reactions Leading to Ribose

This part of the research concerns the use of quantum mechanical calculations and molecular dynamics (MD) simulations to investigate the possible processes and mechanisms involved in the reactions leading to interstellar formation of simple sugars, conducted by Ludwik Adamowicz and post doctoral fellow Eugeniusz Bednarz.

The first part of this project has been devoted to developing new, more accurate methods for modeling stationary states and dynamical behavior of H_2^+ , H_2 , H_3^+ , H_3 and their isotopomers. The reactions leading to simple sugars involve protonated species such as H_3CO^+ , or $CHOCHOCH_2OH_2^+$. The development of new algorithms and computer software is under way, and we expect publications of the first series of results soon. The publications will concern isotopic effects (proton-deuteron exchange) in excited ro-vibrational spectra of the cation hydrogen systems. The study of small hydrogen clusters is a prerequisite to investigating ion-molecule reactions leading to protonated sugars.

Next, we will consider hydrogen/proton exchange between the hydrogen clusters and simple organic molecules leading to formation of organic cations in the gas phase (such as the mentioned above). The goal of the calculations will be to determine the lowest-energy pathways leading from the reactants to the products. This information will be supplied to the molecular dynamics simulation program to calculate reaction rates and equilibrium constants. Since the considered transformations involve small molecular systems, quantum effects may play important roles in accessibility of certain reaction channels. Also hydrogen/proton tunneling has to be taken into consideration, and the classical MD approach may become inadequate.

Highlights

- *Ziurys' group designed and began fabrication of a Fourier transform microwave system spectrometer.*
- *The group conclusively detected simple sugars and their precursors in interstellar gas and comets.*
- *Observations provided evidence of comet fragmentation involving simple organics.*

Module 2: Formation of Habitable Worlds

Najita was awarded time in cycle 1 on the Spitzer Space Telescope (SST) to carry out a program aimed at quantifying gas content in circumstellar disks surrounding stars with ages $t \sim 10$ Myr. The goal is to exploit the wavelength coverage afforded by SST to explore multiple diagnostics sensitive to gas located from the terrestrial planet through giant planet forming regions of disks.

Collaborators on the project are Gorti and Hollenbach (NASA Ames Research Center) and Carr (US Naval Research Laboratory).

Najita, Strom and collaborator Matt Richter (University of California, Irvine) were awarded time (for November 2004) on the NASA Infrared Telescope Facility to carry out a program aimed at defining optimal observing procedures for obtaining high resolution, ultra-high signal/noise spectra of molecular and atomic diagnostics of circumstellar gas.

Najita was awarded time (for November 2004) with the near-infrared cryogenic echelle spectrograph (NIRSPEC) on Keck II to carry out an ambitious program aimed at detecting circumstellar gas and characterizing its kinematics around stars spanning a range of ages from three to thirty Myr.

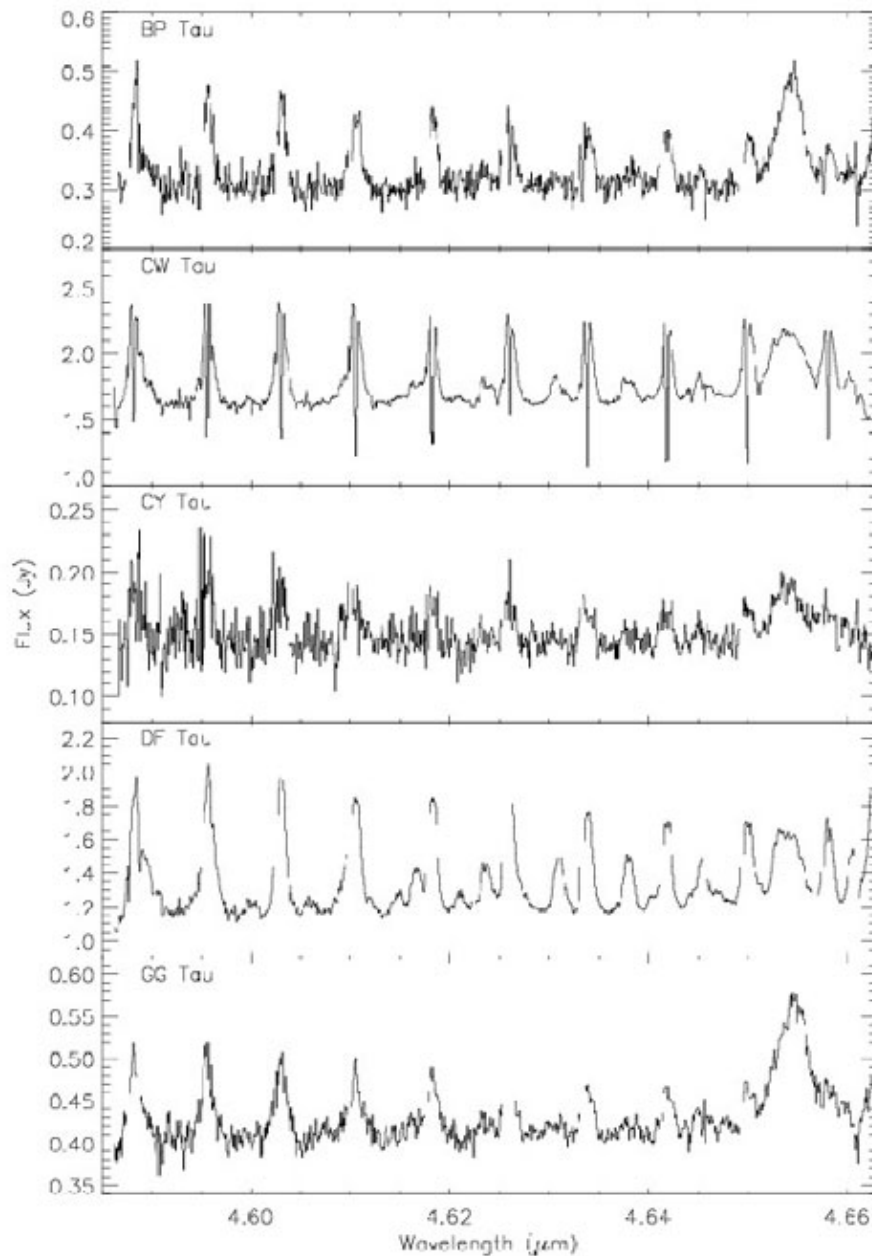


Figure 3: Example of typical spectra of CO fundamental spectra of T Tauri stars observed with NIRSPEC. Results suggest the utility of CO fundamental emission as a probe of disks at planet formation distances. Najita and team will continue such observations using NIRSPEC during this year's observing time.

Najita submitted a paper in collaboration with Glassgold and Igea on the thermochemical structure of optically thick disks.

Meyer continues to lead a Legacy Science Program utilizing data from the Spitzer Space Telescope (SST) entitled "Formation and Evolution of Planetary Systems" (FEPS). Members of the FEPS team involved in LAPLACE include Lunine, Malhotra, Meyer, Najita, and Strom. Initial results from FEPS will appear in a special issue of the Astrophysical Journal set for September. The

paper reports the detection of two debris disks, each with a prominent inner hole in the dust distribution that could be a signpost of planet formation. Through LAPLACE, Meyer and colleagues hope to: i) follow up interesting SST detections with high spatial and spectral resolution ground-based observations; and ii) work with colleagues in the University of Arizona (UA) Lunar and Planetary Lab and elsewhere within the NAI to understand the observed evolution in circumstellar disk properties around sun-like stars in the context of our own solar system evolution. Over 100 stars will be observed with SST in the summer of 2004 and many new results on the evolution of gas and dust disk properties are anticipated. Post-doctoral research associate Daniel Apai will join LAPLACE in September and is expected to play a key role in both areas. Meyer also plans to involve an undergraduate student in this work as part of his senior thesis through the Honors College. Two examples of the potential importance of ground-based observations to help interpret SST observations are the recent work of students Mamajek and Liu. As part of Mamajek's thesis, 10-micron observations were obtained with the Magellan 6.5-m telescope in Chile to characterize disk properties of 10–30 Myr old stars. In a paper to appear in the *Astrophysical Journal*, Mamajek et al. report that dust in the terrestrial planet zone around sun-like stars dissipates on timescales less than 30 Myr. Under the supervision of LAPLACE member Hinz, Liu *et al.* (*Astrophysical Journal* , submitted) resolved the thermal infrared (IR) emission from the disk surrounding the intermediate mass young star HD 100546 using the technique of nulling interferometry. Liu and collaborators have also recently constrained the amount and spatial distribution of thermal IR emission in the Vega debris disk system. Strom and colleagues continue to study the evolution of angular momentum around young sun-like stars and the connection to circumstellar accretion disks and planet formation. While disks play a central role in braking the expected increase in rotation speed of young stars as they contract in radius (conserving angular momentum), it is clear that other factors can also be important. For example, there appear to be differences in the evolution of specific angular momentum between high and low mass stars. Future work on the connection between the presence/absence of disks and rotation in younger protostars as well as older post-accretion stars (10–100 Myr) are underway utilizing ground-based observations as well as the SST.

Giampapa made significant progress in launching the program to monitor stellar activity in clusters spanning a range of ages. The National Optical Astronomy Observatories (NOAO) hired William Sherry as a postdoctoral fellow, and he will be in residence before 1 October 2004. Hardware and software design and purchases for the photometric monitoring component of the program are well underway. Two proposals critical to spectroscopic monitoring were submitted: (1) WIYN 3.5-m/Hydra—Long-Term Proposal: "The Evolution of Activity in Solar-Type Stars" (status: pending), and (2) WIYN 3.5-m/Hydra—Standard Proposal: "Chromospheric Activity at Intermediate Ages" (status: pending). Two papers discussing the telescope hardware and data handling methods for the acquisition and reduction of photometric data are currently in preparation.

Lunine has worked with Raymond and Quinn (University of Washington team) on two papers about the origin of terrestrial planets. For the first paper (*Icarus*,

165), they conducted forty-four simulations of late stage planetary accretion, focusing on the delivery of volatiles (primarily water) to the terrestrial planets. They investigated volatile delivery as a function of Jupiter mass, position and eccentricity, the position of the snow line, and the density (in solids) of the solar nebula. In all simulations, they found that one to four terrestrial planets formed inside 2 astronomical units (AU). These planets vary in mass and volatile content. In the forty-four simulations the models formed forty-three planets between 0.8 and 1.5 AU, including 11 habitable planets between 0.9 and 1.1 AU. These planets range from dry worlds to “water worlds” with 100 + oceans of water ($1 \text{ ocean} = 1.5 \times 10^{24} \text{ g}$), and the planets vary in mass between $0.23M_{\text{Earth}}$ and $3.85M_{\text{Earth}}$.

In the second paper, submitted to *Science*, they conducted simulations of terrestrial planet formation in the presence of “hot Jupiters,” under the assumption of early orbital migration.

They showed that even under these circumstances, terrestrial planets similar to those in the Solar System can form, and can have water contents equal to or higher than the Earth's. For small orbital radii of hot Jupiters (e.g. 0.15, 0.25 AU) potentially habitable planets can form, but for semi-major axes of 0.5 AU or greater their formation is suppressed.

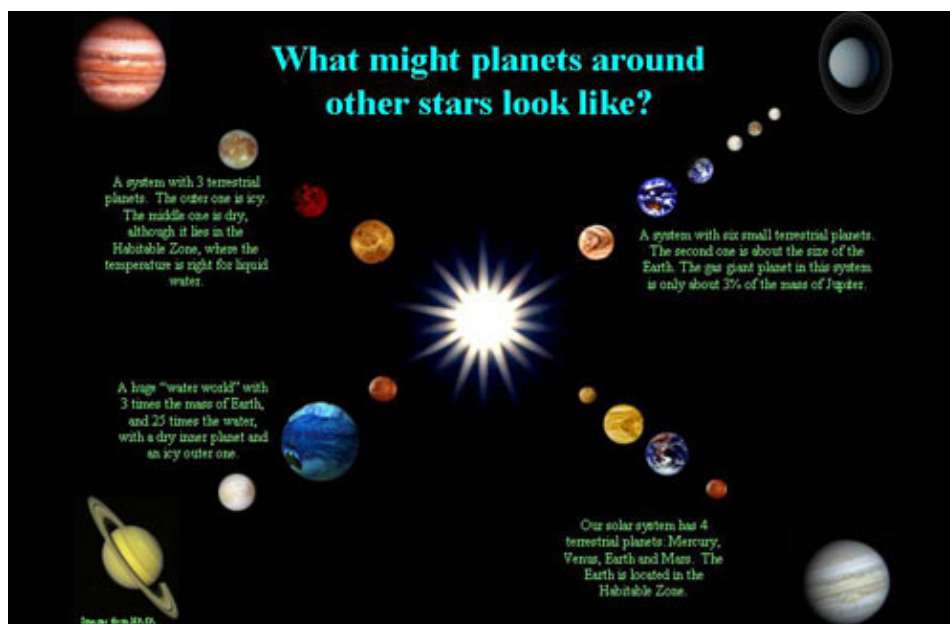


Figure 4: What might planets around stars look like? Lunine and collaborators' simulations of planet formation produce various results for solar system composition.

Malhotra, in collaboration with Kring, Ito and R. Strom, has been investigating the nature of the Late Heavy Bombardment (LHB) of the Moon, ~3.9 Gyr. This group is exploring the possibility that a large catastrophic asteroid break-up event close to a gravitational resonance was responsible for the LHB. They are modeling in detail the dynamics of such a break-up event, calculating synthetic crater records from such an event and confronting these with the observed crater records.

Malhotra and Moro-Martín are studying the expected signatures of planets in debris disks. They have examined the signatures of such features in unresolved stellar spectral energy distribution and their dependence on the planetary debris parameters. They have submitted two papers for publication.

Malhotra has also been studying the stability of orbits of sub-Jovian mass planets. She has developed a simple secular stability criterion for two-planet systems that provides strong constraints on the orbital location of sub-Jovian mass planets.

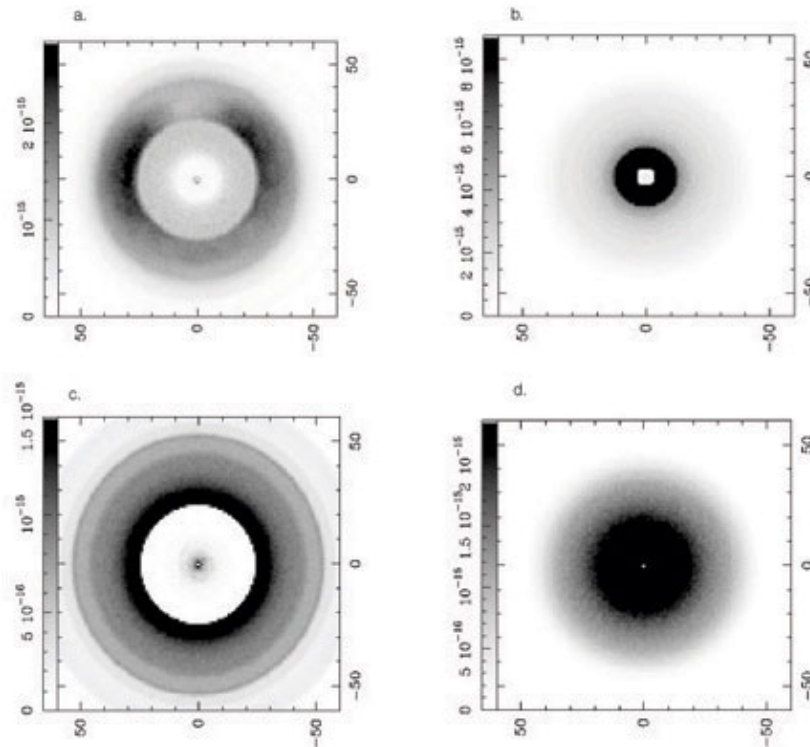


Figure 5: Simulations of dust disks with embedded planets. The figures show the brightness surface density distributions at 70 microns arising from systems with four different planetary configurations: a) Solar System planets; b) single Jupiter mass planet at 5 AU; c) single Jupiter mass planet at 30 AU; d) system with no planets. In all cases the dust-producing planetesimals are between 35 and 50 AU, similar to the Solar System Kuiper Belt.

Highlights

- First results of the Spitzer Legacy program about young disks have been accepted for publication.
- Lunine and collaborators produced models for the origin of terrestrial planets.
- Giampapa and collaborators initiated construction of telescopes for monitoring solar-type stars in clusters.
- Malhotra and collaborators' models have supported observations of debris disks and planet formation.

Module 3: Nature of Planetary Systems

The theoretical program has made rapid progress in the past year towards both modeling expected spectra of giant planets and implementing two distinct search strategies to carry out the first direct detection of these elusive objects. Burrows, Sudarsky and collaborators are building on their successful isolated models for substellar objects to predict brightness and spectra of objects down to planetary masses around other stars. The modeling has integrated stellar irradiation into the calculations, providing predictions for spectra of these objects from the visible into the thermal infrared.

Freed and Hinz are in the process of building an optimized 3–5 micron imager (called Klio) for use with the only thermal-IR optimized adaptive optics system on the 6.5-m MMT. This system will be optimized to detect older, cooler planets in the thermal infrared. First tests of this camera are planned for Fall 2004.

Close and Biller have successfully demonstrated a unique differential technique (Simultaneous Differential Imaging) to detect planets at 1.6 microns by taking advantage of their methane absorption, and have detected a brown dwarf of $\sim 27M_{\text{Jupiter}}$. Observations have begun with the system on the 6.5-m MMT to characterize the prevalence of warm giant planets around nearby young stars.

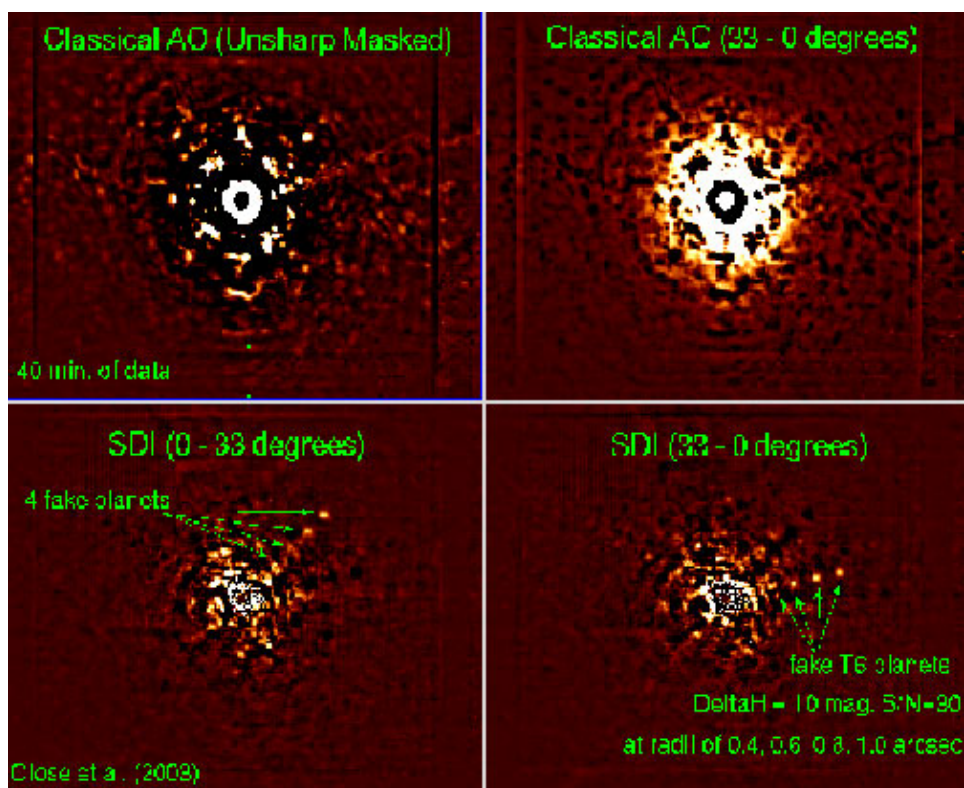


Figure 6: Simulations of Simultaneous Differential Imaging.

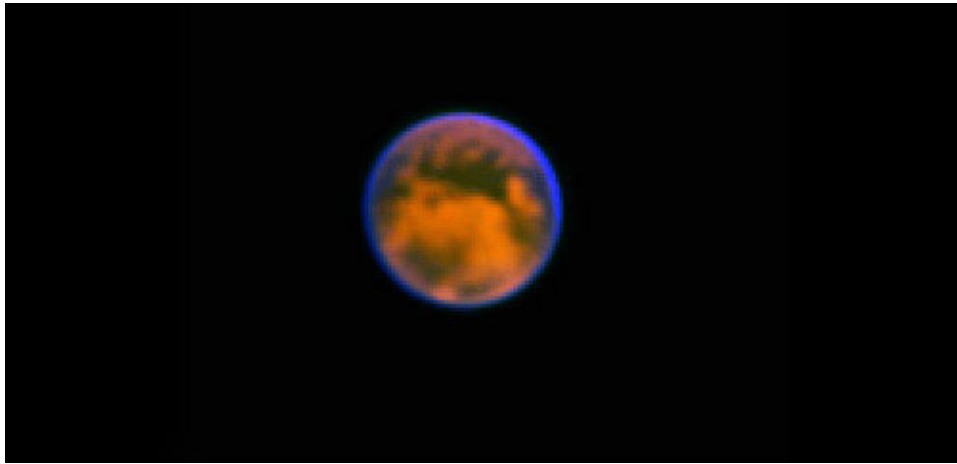


Figure 7: New images of unsurpassed clarity have been obtained with the European Southern Observatory (ESO) Very Large Telescope (VLT) of formations on the surface of Titan, the largest moon in the Saturnian system. They were made by an international research team of Markus Hartung, ESO; Laird Close, University of Arizona; Rainer Lenzen, Max-Planck Institut für Astronomie, Heidelberg, during recent commissioning observations with the "Simultaneous Differential Imager (SDI)", an exoplanet detection device, just installed at the NACO Adaptive Optics instrument. With the high-contrast SDI camera, it is possible to obtain extremely sharp images in three colors simultaneously. Although mainly conceived for exoplanet imaging, this device is also very useful for observations of objects with thick atmospheres in the solar system like Titan. Peering at the same time through a narrow, unobscured near-infrared spectral window in the dense methane atmosphere and an adjacent non-transparent waveband, images were obtained that are virtually uncontaminated by atmospheric components. They map the reflectivity of a large number of surface features in unprecedented detail.

Observations have been made of near infrared earthshine using the 1.8-m Vatican Advanced Technology Telescope (VATT) on Mt. Graham. These observations include one each made in summer and winter (mid-November). For the November observation, the humidity was sufficiently low that the lunar continuum could be clearly seen in the middle of the strong 1.4- and 1.8-micron water bands, despite the air mass of 2-3 times zenith. The spectrum has been measured from 0.7 microns to 2.4 microns. Clearly visible are the 1.27-micron band of oxygen, the CO₂ bands at 2.00 and 2.06 microns as well as near 1.6 microns, the methane band at 2.2 microns and the water bands at 0.94, 1.13, 1.38 and 1.89 microns. The 2.2-micron methane feature seems to be the most easily distinguishable methane feature in the spectrum of the Earth, and so is the most appropriate band for a LifeFinder study. The observations will be part of Margaret Turnbull's thesis, the UA's first astrobiology-oriented Ph.D. thesis.

It is potentially significant that all these features together with those previously reported in the visible earthshine can be seen from the ground at a dry site. We will be exploring the possibility of ground observations of terrestrial planets, particularly at the near IR wavelengths where currently planned Terrestrial Planet Finder (TPF) observations will be limited in angular resolution by the size of mirror that can be incorporated into a space mission. The many possible sites for performing a LifeFinder study will be compared.

Turnbull has developed lists of stars for the Search for Extraterrestrial Intelligence (SETI) program. She has used these same basic lists and information to develop star lists for the TPF missions, working with the TPF science working group. These lists will also be a part of her thesis.

Highlights

Burrows, Sudarsky and collaborators developed self-consistent models of irradiated giant planets that can guide ongoing searches for “other Jupiters.”

Freed and Hinz developed an optimized 3–5 micron camera, called Klio, to detect older giant planets where they are predicted to be relatively bright.

Close and Biller successfully implemented a simultaneous differential imaging technique (SDI) to allow searches for young giant planets in the near infrared.

Woolf and collaborators observed near-infrared earthshine from Mt. Graham, Arizona.

Turnbull and collaborators developed star lists for TPF missions and for SETI.

Module 4 Advancement of Astrobiology

We have initiated our **L**ife **a**nd **PI**anets **A**strobiology **Ce**nter, LAPLACE, and submitted a request to the Arizona Board of Regents for official designation as a UA Center. A UA undergraduate student, David DuPlessis, won the competition for a Center logo. DuPlessis also designed and implemented the LAPLACE website, <http://www.laplace.arizona.edu>.



Figure 8: LAPLACE Logo.

Because LAPLACE did not receive the first NAI funds until November 2003, we did not hold the proposed *2004 Winter School for Astrobiology*. Instead LAPLACE hosted the first *Astrobiology Graduate Student Conference* (ABGRADCON). Details about the conference are available at <http://www.noao.edu/meetings/abgradcon/>. The abstracts for this conference will be permanently available in the journal *Astrobiology*. For the short term they are available at <http://skye.as.arizona.edu/~turnbull/ABGRADCON/GradCon2004.html>, together with a list of seventy-five student contacts. The abstracts are also available through the LAPLACE website, <http://www.laplace.arizona.edu>.

The graduate conference was well attended with about sixty attendees from forty different institutions. There have been a number of follow-up activities. For example, the graduate students who participated in the conference established their own association and website, <http://www.societyforthestudyofastrobiology.com/>.

LAPLACE polled the attendees to determine their preference for the nature of the future *Winter School* effort. The majority of responders indicated a preference for an approximately week-long session, either combined with a graduate student conference (on alternate years) or alone. In light of the experience of ABGRADCON and preferences, LAPLACE is refining its concept of the *Winter School* proposed to NAI to better serve the student population.

Interest in astrobiology at UA is increasing. In addition to ABGRADCON, the NAI-LAPLACE team had a two-day meeting with colleagues from UA life science departments and the Planetary Science Institute (PSI) in order to determine how to expand astrobiology activities in Tucson. Juan Mercader of the Spanish Astrobiology Institute attended, and was especially helpful in

organizing the meeting. One result of the meeting was the submission of a National Science Foundation *Integrative Graduate Education and Research Traineeship* (IGERT) grant proposal to develop life science participation in LAPLACE. UA biologists, Howard Ochman and Nancy Moran, led this effort with support by members of our NAI team. The UA College of Science inducted its first Galileo Circle Fellows in spring 2004. Included in the first four fellows were Jonathan Lunine (Planetary Sciences) and Neville Woolf (Astronomy) from our NAI–LAPLACE team. Additionally, Meyer and Woolf taught a three–unit, one semester graduate course, *Introduction to Astrobiology*, to seventeen students from three UA departments.

The Vatican Observatory Summer School (VOSS) in 2005 will be based on the theme of Astrobiology. Jonathan Lunine is the lead organizer. Staff will also include Woody Sullivan and John Baross of the University of Washington NAI team, Chris Impey and Neville Woolf of UA, and Chris Corbally and George Coyne of the Vatican Observatory.

Impey led a team that successfully obtained a grant from the Templeton Foundation, *Astrobiology and the Sacred: Implications of Life Beyond Earth*. The University of Arizona is one of two universities selected from 200 institutions worldwide to develop this dialogue. This program develops education in the field of astrobiology and has public discussions of the relationship between astrobiology and religion. The key speaker for the first year will be Francisco Ayala. LAPLACE will collaborate with the Templeton Foundation over the grant period to produce thoughtful and systematic reflection on the implications of the search for life. Such work will supplement the LAPLACE astronomical and biological research efforts.

LAPLACE received a five–year \$50,000 private donation for its first astrobiology student scholarships. LAPLACE will use the funds to help graduate students at different points in their careers. The scheme is to provide book scholarships for first year students, travel scholarships for those in the middle of their work, and advanced scholarships to help students in their final years of obtaining their Ph.D.

Our Education and Public Outreach (EPO) program straddles the boundary between traditional public outreach, college non–major education and teacher education. In addition to holding seven workshops for teachers around the country, and two general astrobiology courses for pre–service teachers, it initiated a Master's level course at UA in the summer of 2004 for in–service teachers. We regard this extension of public outreach to undergraduates and teachers as essential for developing future astrobiologists as well as for developing a science–literate public. UA continues to enroll 100–200 students per term in the popular *Life in the Universe* advanced course for nonscience majors. LAPLACE team members play an active role in developing and teaching the course.

Highlights

- *UA will hold the first astrobiology–related Ph.D. defense in summer 2004.*

- LAPLACE hosted ABGRADCON in January 2004.
- UA College of Science submitted an IGERT proposal to NSF.
- UA, University of Washington and the Vatican Observatory are planning the VOSS in astrobiology in 2005.
- UA College of Science selected Lunine and Woolf as Galileo Circle fellows.
- Templeton Foundation awarded a Templeton Research Lectures grant to UA.
- A private donor provided the first astrobiology scholarship funds.
- Meyer and Woolf taught the first astrobiology graduate course.
- EPO submitted six abstracts and one journal article to the Journal of College Science Teaching.
- EPO held two courses, Astrobiology for Teachers, in both the Fall of 2003 and Spring of 2004.
- EPO taught a Master's level course for teachers in the Summer of 2004.
- EPO held seven workshops for teachers around the US.

Roadmap Objectives

- **Objective No. 1.1:** Models of formation and evolution of habitable planets
- **Objective No. 1.2:** Indirect and direct astronomical observations of extrasolar habitable planets
- **Objective No. 3.1:** Sources of prebiotic materials and catalysts
- **Objective No. 4.1:** Earth's early biosphere
- **Objective No. 4.3:** Effects of extraterrestrial events upon the biosphere
- **Objective No. 7.1:** Biosignatures to be sought in Solar System materials
- **Objective No. 7.2:** Biosignatures to be sought in nearby planetary systems